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Article

Socio-Economic Indexes for Water Use in Irrigation in a Representative Basin of the Tropical Semiarid Region

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Abstract: Performance evaluation of irrigated agriculture is an important tool that assists in decision-making on water management in the river basin, particularly in tropical semiarid regions. This study was carried out using information from the Jaguaribe River basin, located in the Northeast region of Brazil, which has an important restriction in the availability of water resources and high competition for water use. From a set of indicators (production, water, economic, and social), the overall performance index of irrigated agriculture was estimated (ranging from zero to 1.0) for two scenarios: high water scarcity and low water scarcity. The performance index used was based on the mean value of these security criteria normalized with respect to the maximum value of the indicator for the crop obtained in the sub-basin. A low performance index of irrigated agriculture (less than 0.3) has always been associated with inadequacy of more than one security indicator. Crops with significant cultivated areas and, therefore, requiring a high volume of irrigation, such as rice, sugar cane, banana, and green coconut, require technical interventions related to the management of the soil–water–plant system aiming at improving yield with less water. Under conditions of water restrictions, crops with performance indexes higher than 0.3 should be prioritized. The study presented here for Jaguaribe River basin may support public policies related to irrigation and agronomic techniques necessary to improve the performance of agricultural under tropical dry lands.

Keywords: irrigated agriculture; water restriction; water productivity; tropical dry lands

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1. Introduction

Improving the management of water resources in agriculture and increasing food production is a priority worldwide, particularly in regions with limited water resources. In irrigated areas, the management strategy should be based on achieving maximum gross margins, considering the sustainable use of resources, without necessarily reaching the maximum yield [1]. The guarantee of food security as well as long-term environmental and economic sustainability has been increasingly threatened by climate change and population growth [2].

Under increasing pressure, the irrigator is compelled to make effective decisions about the irrigation method and corresponding system, irrigation strategy, and method for programming irrigation, among other factors related to water management on the property [3]. According to [4], the current challenge of the rural producer is to ensure that water management in agriculture allows reasonable profits and production of food, fiber, and biofuels in sufficient amounts to meet the demand of the growing population, avoiding unsustainable environmental costs. In this context, irrigated agriculture must be sustainable to ensure its viability [5]. However, the scarcity of water, typical of the arid and semiarid regions, together with the trend of increase in production costs with seeds, fertilizers, pesticides, and energy, imposes uncertainties about the viability of irrigated agriculture.

Optimizing irrigation management requires the development of tools based on decision-making processes, capable of contributing to the planning and management of water resources, aiming at improving public management strategies, within socioeconomic interests. In this direction, it is proposed to evaluate the impact of the different production options on the water consumption of the crop (m^3 ha^{-1}), on physical water productivity (kg m^{-3}) and economic water productivity (BRL m^{-3}), on farm profit (BRL ha^{-1}) [6,7], and on the generation of direct jobs (jobs ha^{-1} and jobs m^{-3}). For this task, it is necessary to analyze indicators of production, water, economic and social security. The use of these indicators enables the improvement of public policies, because it considers not only aspects intrinsically related to the supply, but also economic, social and environmental aspects. Decision-making on farm irrigation improves with the use of physical and economic indicators of water productivity [3,8].

There is still no consensus on the definition and adequacy of the set of indicators and how they should be used to evaluate the performance of irrigated agriculture [3,8]. Irrigators, environmentalists and policy makers generally have different views on what is an efficient use of water in agriculture and how it should be improved [9,10]. While irrigators try to achieve the highest possible profitability in the agricultural activity, environmentalists focus on preserving current water resources and public policy makers work to regulate the demand from different water consumption sectors [3].

Planning actions in the rural sector should follow the recommendations for water resource management and should improve current management models, particularly in tropical semiarid regions. To this end, it is necessary to know and monitor water demand and define indicators and criteria for water use in agriculture and other sectors of the economy, as well as the rules for the operation of reservoirs [11–13]. It is important to consider production security to ensure food production, water security to ensure availability, accessibility and sustainability, economic security to ensure income to the farmer and maintenance of production, and social security to ensure jobs and fixation of rural workers in the field [7,14].

The indicators of production, water, economic, and social security help in the decision-making processes related to irrigated agriculture, focusing on water saving and on results for farmers. However, evaluating them separately may generate contradictory results, since some crops may have high water and production security, but generate less employment and lower income than others [14]. In this context, the definition of a general index, applicable to different scenarios, which assists in decision-making on water management in the river basin, is of great relevance for farmers and for the definition of development policies. However, there are no studies that define a general performance index of irrigated agriculture, particularly in tropical semiarid conditions.

The Jaguaribe River basin is located in the semiarid region of Brazil, which is the main food producing region of the state of Ceará. This basin also has a strategic role in the supply of water to the metropolitan region of Fortaleza (state capital), which is home to about 4 million inhabitants and the largest industries and trade and service companies in the state [15]. This generates several conflicts over water use, and agriculture is heavily penalized in dry years, as observed in the 2012–2016 period [16]. In this context, the objective of this work was to analyze a set of indicators and define a general performance index of irrigated agriculture in the Jaguaribe River basin, representative area of the tropical semiarid region, in order to support decision-making and definition of priorities of water use for irrigation under different water availability scenarios.

2. Irrigated Agriculture Performance Indicators

2.1. Irrigation Efficiency

On field or farm scale, irrigation efficiency (IE) is the ratio between the volume of irrigation water used in a beneficial way (predominantly for crop evapotranspiration and for removal of salts to maintain soil productivity) and the total volume of irrigation water applied, adjusted for variations in soil water storage [17,18]. On an annual basis, the variation of soil water storage in the root zone is often very small, so can be disregarded [19].

The term irrigation consumptive use coefficient (ICUC) to define the fraction of water applied to a field, farm, or project that is converted into vapor or consumed (transpiration plus evaporation from soil surface or plants) [17]. IE and ICUC are physical measures of a given irrigation technology assuming a level of management and, therefore, are not comparable to the terms water use efficiency or water productivity. The unconsumed fraction is 1 ICUC, representing the recoverable portion.

In any water balance study of a project or basin or when estimating the impact of any intervention, both indicators, the consumed fraction and the unconsumed fraction, should be considered [19]. The ICUC indicator is appropriate when considering the water consumed (Crop ET) in the production of the desired effect (crop production), but it is an inappropriate term if the unconsumed water is considered as wasted, since this water is often recovered and reused on a basin scale [20].

2.2. Water Productivity

Considering that dry matter production and transpiration are related to CO_2 and water diffusion processes, [21] defined water use efficiency (WUE) as the relationship between the dry matter production rate (kg ha^{-1} day^{-1}) and the transpiration rate (mm day^{-1}). In daily irrigation practices, physical water productivity (PWP) is a more relevant term than WUE, whose meaning depends on the application. Integrating the rates of dry matter production and transpiration over time, that is, in the crop cycle, leads to biomass yield (kg ha^{-1}) and transpiration (mm), and WUE begins to be expressed by PWP [22]. On a field scale, it is generally difficult to distinguish between transpiration from plants (T) and evaporation from soil and plant surfaces (E). Thus, instead of using T as a basis to define PWP, crop evapotranspiration is used (ET) [22,23].

In agricultural production systems, PWP is used to define the relationship between marketable production of crops and the amount of water consumed in this production (ET), and has served as an indicator to quantify the impact of irrigation calendars in relation to water management. Thus, the total production of biomass (dry matter) is transformed into marketable production of the crop [3,23,24] and PWP is defined with respect to ET (PWP_{ET}), according to Equation (1). PWP_{ET} constitutes the key to the evaluation of deficit irrigation strategies.

$$PWP_{ET} = \frac{\text{Crop marketable yield}}{\text{Crop evapotanspiration}} \rightarrow \frac{Y_M\left(\text{kg ha}^{-1}\right)}{\text{ET (mm)}} \rightarrow \frac{Y_M(\text{kg})}{\text{ET } (\text{m}^3)} \tag{1}$$

On the field scale, the water use represented in the denominator of Equation (1) is often difficult to be determined accurately. Thus, in some situations, other substitutes for PWP are used by many irrigation professionals and, as a consequence, they result in different values. If the total amount of water applied (irrigation (IR) + effective precipitation (EP)) is considered as water consumed by the crop, then Equation (1) can be used to determine physical water productivity (PWP_{IR+EP}) (Equation (2)). The denominator of Equation (2) is a substitute for the water use to obtain the corresponding marketable yield. Under conditions of very low precipitation, such as in arid and semiarid regions, one can convert PWP_{IR+EP} to PWP_{IR} (Equation (3)). In these cases, the variation of soil water storage during the crop cycle, percolation, capillary rise, and surface runoff are disregarded. Many professionals use Equations (2) and (3) to identify differences between irrigation methods and/or irrigation managements.

$$PWP_{IR+EP} = \frac{\text{Crop marketable yield}}{\text{Irrigation volume } + \text{precipitation}} \rightarrow \frac{Y_M(\text{kg})}{\text{IR} + \text{EP } (\text{m}^3)} \tag{2}$$

$$PWP_{IR} = \frac{\text{Crop marketable yield}}{\text{Irrigation volume}} \rightarrow \frac{Y_M(\text{kg})}{\text{IR } (\text{m}^3)} \tag{3}$$

There is a relative consensus about the numerator of PWP being the marketable yield. The total dry or fresh biomass or harvested product can be used in the numerator, expressed in physical or economic terms. However, as the economic values of different agricultural products are not the same, water productivity must be defined economically [8].

A suitable term for the latter is the economic water productivity (EWP), the ratio between products and inputs in monetary terms. For crops with low investment costs, for example cereals, the gross economic irrigation water productivity ($GEWP_{IR}$), which considers the gross margin (gross revenue minus variable costs) is acceptable (Equation (4)) [3]:

$$GEWP_{IR} = \frac{\text{Gross margin}\left(\text{BRL ha}^{-1}\right)}{\text{IR}\ (\text{m}^3\ \text{ha}^{-1})} \tag{4}$$

where the denominator represents only the use of water applied by irrigation.

In the case of woody crops and other crops that require substantial investment from the beginning, the net economic water productivity ($NEWP_{IR}$) is a more appropriate indicator [3], as it considers the net margin instead of the gross margin, that is, it includes variable and fixed costs (Equation (5)):

$$NEWP_{IR} = \frac{\text{Net margin}\left(\text{BRL ha}^{-1}\right)}{\text{IR}\left(\text{m}^3\ \text{ha}^{-1}\right)} \tag{5}$$

Still, neither $GEWP_{IR}$ nor $NEWP_{IR}$ consider the opportunity costs, defined as the benefits lost over the useful life of the crop at a certain interest rate [3]. An appropriate economic analysis should consider the opportunity costs. Therefore, the total economic water productivity (EWP_{IR+EP}), defined by Equation (6), is recommended:

$$EWP_{IR+EP} = \frac{\text{Profit}\left(\text{BRL ha}^{-1}\right)}{\text{IR} + \text{EP}\ (\text{m}^3\ \text{ha}^{-1})} \tag{6}$$

If only the use of irrigation water (IR) is considered in the denominator, then it becomes the economic irrigation water productivity (EWP_{IR})

The profit on the numerator of Equation (6) is defined as gross revenue minus the sum of variable, fixed, and opportunity costs. Thus, EWP_{IR+EP} and EWP_{IR} are adequate to make decisions on the irrigation management of woody crops [3]. It must be pointed out that the lifetime of the crop affects the resulting EWP value, due to its impact on fixed and opportunity costs. This is particularly relevant for fruit tree orchards. Both EWP_{IR+EP} and EWP_{IR} are particularly useful for irrigators who need to make decisions about how to manage irrigation in the most profitable way, that is, when the production target is to increase profitability and not physical water productivity. However, an accurate calculation of EWP_{IR+EP} and EWP_{IR} should be done only at the end of the season, when the revenue and costs are known. Revenue is given by the yield and by the market value, and fixed, variable and opportunity costs must be known for the calculation of total costs [18,25]. This limits the use of EWP_{IR+EP} and EWP_{IR} for decision-making in irrigation, since the economic evaluation must be made before the beginning of the irrigation season. The challenge is greater when the value of the yield depends on the quality of the product and when the price of some ingredients, such as energy, fertilizers, and pesticides, varies from one season to another and even during the growing period [3].

Water productivity indicators express the benefits derived from water consumption by crops and can be used to assess the impact of agricultural exploitation strategies under water scarcity conditions. They provide an adequate view of where and when water could be saved. These indicators are also useful for inferring about the potential increase in crop yield that may result from increased water availability.

3. Case Study—Irrigated Agriculture in the Jaguaribe River Basin—CE, Brazil

3.1. Location and Characterization of the Jaguaribe River Basin

The Jaguaribe River basin is located in the Northeast region of Brazil, with a total drainage area of 72,645 km^2, corresponding to about 48% of the Ceará State territory. The basin is within an area of tropical semiarid climate and has low perspective in groundwater reserves, because almost all of its area is located on crystalline rocks of low water potential [26]. This basin is subdivided into five sub-basins (Salgado, Banabuiú, Upper, Medium, and Lower Jaguaribe), and the present study focuses on the three sub-basins associated with the main river (Figure 1): Lower Jaguaribe (LJ), Medium Jaguaribe (MJ), and Upper Jaguaribe (UJ).

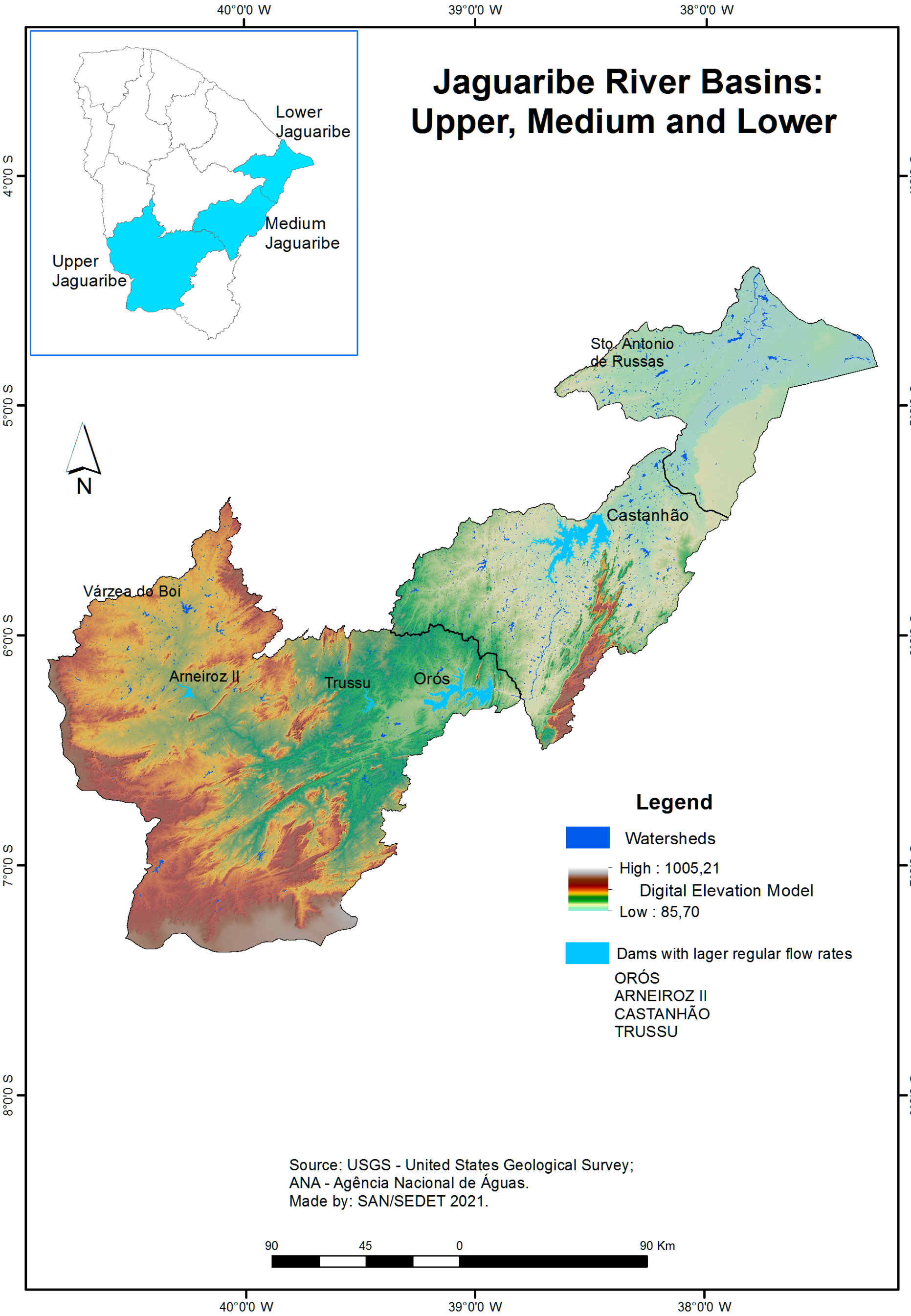

Figure 1. Schematic representation of the three sub-basins of the Jaguaribe River basin—CE, Brazil.

The LJ sub-basin is located in the eastern part of the Ceará State, with a drainage area of 5452 km^2. The average annual rainfall varies between the municipalities and, in 2017, the annual average of the rain gauge stations of the LJ sub-basin was 648 mm, of which 88.2% occurred in the months from February to May [27]. The annual average reference evapotranspiration ranged from 1346 to 1933 mm between municipalities. It has a reservoir with capacity to accumulate 24,000,000 m^3 of water [28]. Although the LJ sub-basin has the smallest area among all Jaguaribe River sub-basins, it is of great importance in the context of water resources. The amount of water required for irrigation is quite representative relative to the total volume of water demanded throughout the basin [14].

The MJ sub-basin is located in the eastern part of the Ceará State and has a drainage area of 10,376 km^2, with 13 dams and water accumulation capacity of 6860,905,600 m^3 [29]. The average annual rainfall in 2017 was 577.3 mm, with 75.5% occurring between February and May [27]. The annual average reference evapotranspiration varied among the municipalities from 1885 to 2020 mm.

The UJ sub-basin is located in the southwestern part of the Ceará State, drains an area of 24,636 km^2 and has water storage capacity of 2792,563,000 m^3, with 18 reservoirs [30]. The average rainfall in 2017 was 489 mm, 70.7% of this value between February and May [27], and the annual reference evapotranspiration ranged from 1696 to 2020 mm.

3.2. Data Source

The project used 2017 data for the Upper, Medium, and Lower Jaguaribe sub-basins, made available in the study of indicators published by ADECE [12]. The data of agricultural production in the sub-basins were obtained by performing a complete register of water users and using the Irrigator Advisory System (*Sistema de Assessoramento ao Irrigante*—S@I) [31]. The data of agricultural production in the sub-basins were surveyed from farmers, producer associations, irrigation districts, Ceará State Technical Assistance and Rural Extension Company (*Empresa de Assistência Técnica e Extensão Rural do Ceará*—EMATERCE) and registrations of users of the Ceará State Water Resources Management Company (*Companhia de Gestão dos Recursos Hídricos do Ceará*—COGERH). The information allowed the preparation of a complete register, entered according to the needs of the computer tool used: *Sistema de Assessoramento ao Irrigante*—S@I [31]. Weather information was provided by the Ceará State Foundation for Meteorology and Water Resources (FUNCEME), with data from the automatic stations monitored in the basins [27].

3.3. Irrigated Agriculture in the Jaguaribe River Basin

Table 1 shows the crops and their irrigated areas in the Jaguaribe River sub-basins, using the 2017 database [12]. The irrigated area in the Jaguaribe River basin was 22,939 ha, comprising 19,974 ha in LJ, 1353 ha in MJ, and 1612 ha in UJ. Although LJ has the smallest drained area, it stands out with the largest irrigated area. Of the 24 irrigated crops in this sub-basin, 15 are permanent and occupied 43.13% of the total area, and 9 are temporary with 56.87% of the total area. Among the permanent crops, banana occupied the largest area (53.51%) and, among the temporary crops, the largest area was occupied by melon (30.12%). In the entire Jaguaribe River basin, among the 24 irrigated crops, 16 are fruit crops, occupying 71.43% of the total area.

The total volume of irrigation applied (Table 1) was estimated by the Ceará State Development Agency [12] as being an average value of the Jaguaribe River basin. It was verified that the total volume applied in the basin was 344,255.86 $\times$ 10^3 m^3, 47.79% in permanent crops and 52.21% in temporary crops. The volume applied to fruit crops was 283,585.45 $\times$ 10^3 m^3 (69.30% of the total) and, from this, the banana crop received the largest amount (27.68% of the total volume of the basin), being cultivated mainly in LJ (21.8% of the total cultivated area in the sub-basin).

Table 1. Crops, irrigated areas and gross irrigation volumes applied in the Jaguaribe River sub-basins in 2017. Data sources: [12,32].

Crops	Irrigated Areas (ha) *			Total	VA ** (m^3 ha^{-1})	Predominant Irrigation System
	LJ	MJ	UJ			
Avocado	15	—	4	19	19,000	Drip
Barbados cherry	333	20	—	353	18,000	Micro-sprinkler
Rice	1455	265	340	2060	28,000	Flooding ***
Custard apple	5			5	10,570	Drip
Banana	4359	336	599	5294	18,000	Micro-sprinkler
Sweet potato	34	25	—	59	10,490	Sprinkler ****
Cashew	46	—	—	46	7000	Drip
Sugar cane	880	—	2	882	19,000	Center pivot
Green coconut	1115	56	66	1237	15,000	Micro-sprinkler
Cowpea*	1651	427	255	2333	7500	Sprinkler ****
Guava	801	60	54	915	15,000	Drip
Soursop	31	—	—	31	23,000	Micro-sprinkler
Orange	169	3	6	178	16,500	Drip
Lemon	314	72	1	387	14,000	Drip
Cassava	168	34	58	260	7200	Sprinkler ****
Papaya	865	—	14	879	15,000	Drip
Mango	382	2	—	384	14,000	Micro-sprinkler
Passion fruit	104	—	35	139	14,000	Drip
Watermelon	2574	—	4	2578	12,000	Drip
Melon	3929	—	—	3929	11,000	Drip
Green corn	683	49	126	858	12.000	Sprinkler ***
Cactus pear	16	—	—	16	5500	Drip
Tomato	34	4	48	86	10,000	Drip
Grape	11	—	—	11	17,600	Drip
Total	19,974	1353	1612	22,939	339,360	

* Area corresponding to two crop seasons per year in LJ (Lower Jaguaribe), MJ (Medium Jaguaribe) and UJ (Upper Jaguaribe); ** VA—Gross irrigation volume applied, *** Continuous flooding, **** Conventional sprinkler irrigation systems.

3.4. Production and Irrigation Requirement in the Jaguaribe River Basin

Table 2 shows the physical land productivity (PLP) for each crop in the three sub-basins. The volume of irrigation required by the crops (VR) was estimated based on the potential evapotranspiration of each crop (ET_c). The Penman–Monteith method published in FAO Bulletin 56 [33] was used to calculate the reference evapotranspiration (ET_0). Crop coefficients (K_c) were those published by FAO 56, adapted to the climatic conditions of the region. The data used to calculate ET_0 in each of the sub-basins were obtained from eight weather stations belonging to the National Institute of Meteorology (*Instituto Nacional de Meteorologia*—INMET), located in the study region. The S@I system [31] was the Decision Support System used to determine the ET_c in the municipalities of each sub-basin.

According to Tables 1 and 2, 84.1% of the irrigated area in LJ was occupied with eight crops (1/3 of the crops): banana, melon, watermelon, cowpea, rice, green coconut, sugar cane, and papaya. These crops received a gross irrigation volume equivalent to 85.2% of the total volume in the sub-basin and produced 93.2% of total production. The estimated volume required by these eight crops corresponded to 84.5% of the total of the sub-basin. Three crops received irrigation deficit: cowpea (10%), cassava (24%), and cactus pear (51%).

In the MJ sub-basin, 85.74% of the irrigated area was occupied with five main crops: rice, banana, cowpea, guava and lemon. This group of crops received 88.5% of the gross irrigation volume and produced 82.8% of the total production of the sub-basin. The estimated required volume in the sub-basin was 18,562.1 $\times$ 10^3 m^3, while the gross volume applied was 20,991.1 $\times$ 10^3 m^3. However, PLP was low for most crops.

Table 2. Actual (PLP) and maximum (PLPmax) physical land productivity, and estimated net need for irrigation (VR, m^3 ha^{-1}) in the Jaguaribe River basin. Data sources for PLP: [12,32].

Crops	PLP				VR		
	LJ	MJ	UJ	PLP Max *	LJ	MJ	UJ
	(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	(m^3 ha^{-1})	(m^3 ha^{-1})	(m^3 ha^{-1})
Avocado	10,200	—	3750	11,000	9840	—	8310
Barbados cherry	24,300	7000	—	24,300	11,760	14,280	—
Rice	13,400	5774	4220	13,400	13,200	15,720	10,920
Custard apple	4400	—	—	4400	10,041	—	—
Banana	23,807	31,917	26,668	31,917	14,240	17,440	12,220
Sweet potato	10,485	25,000	—	25,400	5220	12,864	—
Cashew	4098	—	—	4098	7040	—	—
Sugar cane	61,393	—	55,834	61,393	7250	—	6210
Green coconut	20,706	21,600	35,000	35,000	10,000	12,300	8790
Cowpea	1500	1200	1288	1920	8330	10,190	7060
Guava	15,625	25,300	22,412	33,000	8840	10,700	7740
Soursop	7086	—	—	7086	9840	—	—
Orange	13,100	2000	8000	13,100	11,75	14,280	9850
Lemon	11,200	7200	4000	11,200	11,860	14,280	9768
Cassava	23,000	21,400	30,000	31,000	9470	11,420	7900
Papaya	78,000	—	59,556	78,000	10,320	—	8610
Mango	13,100	11,500	—	20,475	11,250	14,280	—
Passion fruit	25,780	—	25,000	25,780	11,590	—	10,596
Watermelon	65,800	—	48,455	65,800	6880	—	5800
Melon	68,750	—	—	68,750	7350	—	—
Green corn	9407	6151	9531	9531	8100	9650	6540
Cactus pear	216,180	—	—	250,000	11,295	—	—
Tomato	84,530	35,000	64,000	84,530	5890	7140	4920
Grape	10,545	—	—	34,625	9840	—	—
Total(ha) (×1000) M **	761,412.3	17,976.8	29,351.9		198,601.4	18,562.1	43,841.8

* maximum values observed in the Jaguaribe River basin; ** sum of the product between physical land productivity and irrigated area. LJ (Lower Jaguaribe), MJ (Medium Jaguaribe), and UJ (Upper Jaguaribe).

The fifteen irrigated crops in the UJ occupied an area of 1612 ha, received a gross irrigation volume of 27,399.1 × 10^3 m^3, while the required volume was 15,912.6 × 10^3 m^3, and generated a total production of 29,351.9 kg. About 85.98% of the area was occupied with five crops: banana, rice, cowpea, corn and coconut. These five crops received 90.2% of the gross irrigation volume, required 89.1% of the water volume and were responsible for 72.7% of the total production.

3.5. Net Revenue per Unit of Area

The net revenues per unit of area (ELP, economic land productivity) were calculated for irrigated crops in each producing municipality of the Jaguaribe River basin and the average value of the sub-basins was obtained (Table 3). Using questionnaires distributed to rural producers, the average values of the number of jobs generated per unit of area (LLAB) were estimated for each of the agricultural activities in the sub-basins studied [34].

Production costs were formed by the following components, as reported by the ADECE [12]: (a) costs of the inputs used in the production—seedlings/seeds, fertilizers, and pesticides; (b) cost of water—amortization of investment in commonly used hydraulic structures, administration, operation, conservation, and maintenance of existing infrastructure and electricity; (c) cost of mechanization—plowing, harrowing, spraying with tractor, and transportation; (d) cost of variable labor—irrigation management, fertilization, planting and replanting, crop monitoring, harvesting, selection, and packaging; (e) cost of administration—management and technical assistance; (f) cost of irrigation equipment—

annual rate of amortization and maintenance; and (g) interest on the fixed capital (inputs + mechanization + variable labor).

Table 3. Average net revenue (ELP) and maximum net revenue (ELPmax), average number of jobs (LLAB) and maximum number of jobs (LLABmax) per hectare in the Jaguaribe River basin. Amounts expressed in Reais (BRL), Brazilian currency.

Crops	ELP (BRL ha^{-1})				LLAB (jobs ha^{-1})			
				ELP *				LLAB *
	LJ	MJ	UJ	Max	LJ	MJ	UJ	Max
Avocado	10,404	—	9375	19,017	0.98	—	0.75	0.98
Barbados cherry	11,047	9800	—	45,460	1.90	1.62	—	1.90
Rice	5065	5165	5584	5584	0.54	0.68	0.65	0.75
Custard apple	33,440	—	—	33,440	0.58	—	—	0.58
Banana	21,627	20,698	51,132	51,132	0.41	0.58	0.57	0.58
Sweet potato	12,494	17,600	—	21,856	1.10	1.24	—	1.38
Cashew	10,772	—	—	10,772	0.16	—	—	0.16
Sugar cane	3350	—	11,115	11,115	0.14	—	0.18	0.18
Green coconut	7820	7859	8113	11,043	0.18	0.18	0.32	0.32
Cowpea	2079	1928	1822.5	2705	1.24	0.98	1.15	1.24
Guava	18,909	35,410	31,670	35,410	0.92	0.71	0.30	0.92
Soursop	16,544	—	—	16,544	0.65	—	—	0.65
Orange	7128	3867	11,667	15,047	0.49	0.36	0.29	0.49
Lemon	6792	2208	4000	20,578	0.30	0.42	0.61	0.61
Cassava	16,293	23,961	33,978	33,978	0.86	0.42	0.60	0.86
Papaya	42,002	—	29,929	42,002	0.53	—	0.50	0.62
Mango	15,445	8050	—	23,251	0.40	0.52	—	0.52
Passion fruit	75,700	—	20,546	75,700	0.41	—	0.41	0.41
Watermelon	3917	—	20,700	20,700	0.66	—	0.80	0.80
Melon	22,253	—	—	22,253	0.72	—	—	0.72
Green corn	7757	6711	18,752	18,752	1.12	0.80	0.78	1.20
Cactus pear	42,727	—	—	42,727	0.80	—	—	0.80
Tomato	69,168	35,000	51,079	69,168	3.26	3.10	3.15	3.26
Grape	26,785	—	—	86,333	2.31	—	—	2.31
Total (BRL) (×1000) **	299,493.4	13,817.2	43,377.1		12,768	1008	1208	

* maximum values observed in the Jaguaribe River basin; ** sum of the product between ELP and irrigated area. LJ (Lower Jaguaribe), MJ (Medium Jaguaribe), and UJ (Upper Jaguaribe).

The gross value of the production was calculated by the product between yield (kg ha^{-1}) and the average price of production (BRL kg^{-1}). In this case, the average exported amount and the average export price, the amount commercialized in markets in other states of the federation and the average price of CEAGESP, and the amount marketed in the domestic market and the average price of CEASA-CE were considered. The difference between the gross production value and the production costs resulted in net revenue (Table 3).

In 2017, in LJ the total net revenue of BRL 299,493,400 (Table 3) was obtained with a total production of 761,412.3 × 10^3 kg and a gross irrigation volume of 295,595.8 × 10^3 m^3, that is, BRL 1.03 m^{-3} and 2.584 kg m^{-3}. In MJ, the total amount of production (17,976.8 × 10^3 kg) was obtained with 20,991.1 × 10^3 m^3 of water, generating a total net revenue of BRL 13,817,200, that is, BRL 0.70 m^{-3} and 0.881 kg m^{-3}. In UJ, 29,351.9 × 10^3 kg were produced with an irrigation volume of 27,399.1 m^3, resulting in a net revenue of BRL 43,377,100, which corresponds to BRL 1.58 m^{-3} and 1.07 kg m^{-3}. In UJ, the highest physical and economic water productivities were obtained, although the highest gross volume of irrigation compared to the required volume was used.

3.6. Performance Indicators of Irrigated Agriculture in the Jaguaribe River Basin

The performance of irrigated crops was analyzed using the following indicators, grouped into four classes: (a) production security—land productivity (kg ha^{-1}) and water productivity (kg m^{-3}), (b) economic security—economic land productivity (BRL ha^{-1}) and economic applied water productivity (BRL m^{-3}), (c) social security—number of jobs generated per unit of area (jobs ha^{-1}) and per unit of volume of water applied (jobs m^{-3}), and (d) crop cycle, considering that permanent crops represent a heritage of the agricultural property and should be given priority of salvation under conditions of water scarcity.

The relative irrigation supply (RIS) was defined as the relationship between the amount of irrigation applied in crop i in the sub-basin j (VA_{ij}, m^3 ha^{-1}) and the amount of water required by the crop (VR_{ij}), estimated by crop evapotranspiration (Equation (7)).

$$RIS_{ij} = \frac{VA_{ij}}{VR_{ij}} \tag{7}$$

The RIS estimates made here are approximate because the gross volumes applied to crops (VA) represent general information presented in the report of ADECE [12], revealing the need for comprehensive accounting of water on field scale and on basin scale.

To formulate a general performance index of irrigated agriculture (I), the following productivity indicators were used, normalized by the value of the indicator for cultivation with maximum value:

(a) Production security: the two indicators are:

(a_1) Physical land productivity ratio ($PLPR_{ij}$):

$$PLPR_{ij} = \frac{PLP_{i,j}}{PLP_{\ max}} \tag{8}$$

where PLP_{ij} is the physical land productivity (kg ha^{-1}) of crop i in the sub-basin j, and PLP_{max} is the maximum physical land productivity (kg ha^{-1}) observed in the sub-basin.

(a_2) Physical water productivity ratio ($PWPR_{ij}$):

$$PWPR_{ij} = \frac{PWP_{i,j}}{PWP_{max}} \tag{9}$$

where $PWP_{i,j}$ is the physical water productivity (kg m^{-3}) of crop i in sub-basin j, and PWP_{max} is the maximum physical water productivity (kg m^{-3}) observed in the sub-basin.

(b) Economic security: the two indicators are:

(b_1) Economic land productivity ratio ($ELPR_{ij}$):

$$ELPR_{ij} = \frac{ELP_{i,j}}{ELP_{max}} \tag{10}$$

where $ELP_{i,j}$ is the economic land productivity (BRL ha^{-1}) of crop i in the sub-basin j, and ELP_{max} is the maximum economic land productivity (BRL ha^{-1}) observed in the sub-basin.

(b_2) Economic water productivity ratio ($EWPR_{ij}$):

$$EWPR_{ij} = \frac{EWP_{i,j}}{EWP_{max}} \tag{11}$$

where $EWP_{i,j}$ is the economic water productivity (BRL m^{-3}) of crop i in the sub-basin j, and EWP_{max} is the maximum economic water productivity (BRL m^{-3}) observed in the sub-basin.

(c) Social Security: the two indicators are:

(c_1) Ratio of number of jobs generated per unit of area ($LLABR_{ij}$):

$$LLABR_{ij} = \frac{LLAB_{i,j}}{LLAB_{max}} \tag{12}$$

where $LLAB_{i,j}$ is the number of jobs generated per unit of area (jobs ha^{-1}) by crop i in the sub-basin j, and $LLAB_{max}$ is the maximum number of jobs generated per unit of area (jobs ha^{-1}) observed in the sub-basin.

(c_2) Ratio of number of jobs generated per unit of water volume applied ($WLABR_{ij}$):

$$WLABR_{ij} = \frac{WLAB_{i,j}}{WLAB_{max}} \tag{13}$$

where $WLAB_{i,j}$ is the number of jobs generated per unit of water volume applied (jobs m^{-3}) by crop i in the sub-basin j, and $WLAB_{max}$ is the maximum number of jobs generated per unit of water volume applied (jobs m^{-3}) observed in the sub-basin.

(d) Crop cycle (C)

Permanent crops: $C_i = 1.0$

Long-cycle temporary crops (cycle $\geq$ 180 days): $C_i = 0.75$

Short-cycle temporary crops (cycle $<$ 180 days): $C_i = 0.5$

where C_i is the weight assigned to crop i, referring to the length of the cycle.

For the public administration to identify the crops that could be favored and those that should not be encouraged, from a given scenario of water scarcity, the following performance index was proposed (PI_{ij}) for irrigated crop i in sub-basin j (Equation (14)):

$$\begin{aligned} PI_{ij} = \alpha_1 PLPR_{ij} \quad & +\alpha_2 PWPR_{ij} + \alpha_3 ELPR_{ij} + \alpha_4 EWPR_{ij} \\ & +\alpha_5 LLABR_{ij} + \alpha_6 WLABR_{ij} + \alpha_7 C_i \end{aligned} \tag{14}$$

where α_k is the weights assigned by the manager to each security ratio according to his/her priorities and $\alpha_1 + \alpha_2 + \ldots + \alpha_7 = 1$. The closer to 1, the better the performance of the irrigated crop and, as I_{ij} decreases, it means that one or more security ratios are low and the agricultural activity needs some improvement intervention. The index PI_{ij} serves to prioritize irrigated agricultural activities in different scenarios of water scarcity.

4. Results and Discussion

4.1. Relative Irrigation Supply

In the LJ, of the 24 irrigated crops in 2017, 15 (62.5%) showed RIS above 1.43 (Table 4). Sugar cane (2.62) irrigated by center pivot, soursop (2.34) irrigated by micro-sprinkler, and rice (2.12) irrigated by continuous flooding stood out with very high values. However, research conducted with rice crop in the Morada Nova irrigated perimeter, shows that irrigation management with intermittent flooding can significantly reduce RIS, because in this type of management the gross volume of irrigation is significantly reduced, reaching 30 to 40% of the total volume of water applied in continuous flood irrigation [35]. Sugar cane and soursop crops, although conducted under high-tech irrigation systems, require efficient irrigation management techniques, including avoiding water application at times of high solar radiation and strong winds. There were six crops (25%) with RIS between 1.0 and 1.43 and three crops (12.5%) with RIS lower than 1.0 (cowpea, cassava, and cactus pear), indicating deficit irrigation.

In MJ, only the rice crop irrigated by continuous flooding showed RIS higher than 1.43 (1.78). In this sub-basin, five crops had RIS lower than 1 (sweet potato, cowpea, lemon, cassava, and mango), indicating that they received deficit irrigation. In UJ, among the 15 irrigated crops, 11 had RIS above 1.43, especially avocado (micro-sprinkler), rice (continuous flooding), sugar cane (center pivot), watermelon (drip), and tomato (drip), with values greater than 2.0. Only cassava received deficit irrigation. Such very high values of RIS illustrate typical problems of water application. These problems emphasize the need to strictly consider irrigation management techniques, selection of soils suitable for cultivation under flooding, adequate projects of the systems, adequate techniques for the operation of irrigation projects, program for maintenance of irrigation systems, and training of irrigators. Good irrigation management requires water application at the right time and in adequate quantities to meet different water needs of crops [19].

Table 4. Relative irrigation supply in the three Jaguaribe River sub-basins.

Crops	RIS			Crops	RIS		
	LJ *	MJ	UJ		LJ	MJ	UJ
Avocado	1.93	—	2.29	Orange	1.40	1.16	1.73
Barbados cherry	1.53	1.26	—	Lemon	1.18	0.98	1.43
Rice	2.12	1.78	2.56	Cassava	0.76	0.62	0.91
Custard apple	1.05	—	—	Papaya	1.45	—	0.57
Banana	1.26	1.03	1.47	Mango	1.24	0.98	—
Sweet potato	2.01	0.82	—	Passion fruit	1.21	—	1.32
Cashew	1.00	—	—	Watermelon	1.75	—	2.07
Sugar cane	2.62	—	3.06	Melon	1.50	—	—
Green coconut	1.50	1.22	1.71	Green corn	1.48	1.24	1.84
Cowpea	0.90	0.74	1.06	Cactus pear	0.49	—	—
Guava	1.70	1.40	1.94	Tomato	1.70	1.40	2.03
Soursop	2.34	—	—	Grape	1.79	—	—

* LJ (Lower Jaguaribe), MJ (Medium Jaguaribe), and UJ (Upper Jaguaribe).

It is important to note that water saved on a farm scale does not normally reduce water consumption on the basin scale. Increments in irrigation efficiency for cultivated fields are rarely associated with increased water availability on a larger scale [23]; an increase in irrigation efficiency that reduces water extractions can have a negligible effect on water consumption [20,36]. The claim that an increase in irrigation efficiency on field scale does not increase water availability on a basin scale is explained by the fact that losses of water not previously consumed on an agricultural scale (e.g., runoff) are often recovered and reused on a watershed scale [8,10,37]. Although the actual water saving at basin level is limited, it does not mean denying the reasons why one should opt for a level of irrigation management that allows for a low RIS, increase in crop yield and income, reduction in irrigation costs, reduction in nutrient leaching, and the possibility of increasing the irrigated area and allocating water to crops of higher value.

4.2. Physical and Economic Water Productivity and Generation of Jobs

Table 5 shows the physical and economic water productivity for irrigated crops in three sub-basins of the Jaguaribe River in 2017. For physical water productivity, the volume of water applied by irrigation (VA) to the crops of each sub-basin was considered. For economic water productivity, the net revenue obtained from crop production was considered. Opportunity costs were not computed.

In LJ, the main agricultural area of the basin, rice crop has a relatively high PLP (13,400 kg ha^{-1}) as compared to the other sub-basins. PWP was equal to 0.479 kg m^{-3}, which is comparable to the average value of 0.43 kg m^{-3} verified with continuous flooding and application of a gross volume of 13,760 m^3 ha^{-1} in silty-clayey-textured soils in the Morada Nova irrigated perimeter, LJ sub-basin [38]. The increase in PWP can be achieved both by reducing the volume of water applied and by increasing the yield for the same amount of water [39]. Figure 2A shows the relationship between PWP and RIS for some crops selected in LJ. It is observed that cactus pear is the most productive crop regarding water use, although it is irrigated with a volume lower than the net need for maximum yield. However, this crop has a small cultivated area (16 ha). Cowpea, with a significant cultivated area (1651 ha), is irrigated with deficit but resulted in low physical water productivity. On the other hand, more extensive crops such as rice and sugar cane, among others, receive a much higher water supply than the net needs and result in low physical productivity.

Except for cactus pear, crops that have the best physical water productivities are tomato, melon, papaya and watermelon, although they have received an irrigation volume of at least 1.45 times the net irrigation needs.

Table 5. Physical (PWP) and economic (EWP) water productivity in the sub-basins of the Jaguaribe River.

Crops	LJ *		MJ		UJ		PWP	EWP
	PWP	EWP	PWP	EWP	PWP	EWP	Max	Max
	(kg m^{-3})	(BRL m^{-3})	(kg m^{-3})	(BRL m^{-3})	(kg m^{-3})	(BRL m^{-3})	(kg m^{-3})	(BRL m^{-3})
Avocado	0.537	0.55	—	—	0.197	0.49	0.579	1.00
Barbados cherry	1.350	0.61	0.389	0.54	—	—	1.350	2.53
Rice	0.479	0.18	0.206	0.14	0.151	0.20	0.479	0.20
Custard apple	0.416	3.16	—	—	—	—	0.416	3.16
Banana	1.323	1.20	1.773	1.15	1.482	2.84	1.773	2.84
Sweet potato	0.997	1.19	2.383	1.68	—	—	2.421	2.08
Cashew	0.585	1.54	—	—	—	—	0.585	1.54
Sugar cane	3.231	0.18	—	—	2.939	0.58	3.231	0.58
Green coconut	1.330	0.52	1.440	0.52	2.333	0.54	2.333	0.74
Cowpea	0.200	0.28	0.161	0.26	0.172	0.24	0.256	0.36
Guava	1.042	1.26	1.688	2.36	1.494	2.11	2.200	2.36
Soursop	0.308	0.72	—	—	—	—	0.308	0.72
Orange	0.794	0.43	0.121	0.23	0.484	0.71	0.794	0.91
Lemon	0.800	0.48	0.477	0.16	0.286	0.29	0.800	1.47
Cassava	3.194	2.26	2.972	3.33	4.168	4.72	4.306	4.72
Papaya	5.200	2.80	—	—	3.970	1.99	5.200	2.80
Mango	0.936	1.10	0.821	0.58	—	—	1.463	1.66
Passion fruit	1.841	5.41	—	—	1.786	1.47	1.841	5.41
Watermelon	5.483	0.33	—	—	4.083	1.72	5.483	1.72
Melon	6.250	2.02	—	—	—	—	6.250	2.02
Green corn	0.784	0.65	0.513	0.56	0.794	1.56	0.794	1.56
Cactus pear	39.306	7.77	—	—	—	—	39.306	7.77
Tomato	8.453	6.92	3.500	3.50	6.400	5.11	8.453	6.92
Grape	0.599	1.52	—	—	—	—	1.967	4.90
Mean	2.584	1.03	0.881	0.70	1.070	1.58		

* LJ (Lower Jaguaribe), MJ (Medium Jaguaribe), and UJ (Upper Jaguaribe).

It is observed that EWP for rice and sugar cane was low in all sub-basins, because net revenue per hectare (ELP) from the cultivation was low and the gross volume of irrigation applied was high. On the other hand, under intermittent flooding, [35] obtained for rice EWP between BRL 0.74 and BRL 0.82 m^{-3} in an area located in LJ. Figure 2B shows a sample of EWP as a function of RIS, for some crops selected in LJ. It is observed, again, that cactus pear showed high economic water productivity, although it was irrigated with a volume of almost half of the net volume required. Crops such as tomato and passion fruit showed good values of EWP, but they were irrigated with water volumes of 1.7 and 1.2 times the required volume. On the contrary, rice and sugar cane crops received irrigation volumes significantly higher than the required volumes (2.2 and 2.6 times) and resulted in low values of EWP.

It should also be highlighted that the low social contribution of sugar cane, green coconut, and rice cultivation in the region, generating along the year 0.007, 0.012, and 0.019 jobs per 1000 m^3 of water applied, in LJ (Figure 2C). It is observed that the tomato crop generates the highest number of jobs per 1000 m^3 of applied water, although RIS is high (1.7). Cowpea has a good social contribution (0.9 jobs per 1000 m^3), and was irrigated with deficit. Cactus pear irrigated with deficit (RIS = 0.49), which stood out in the previous indicators, in this case does not have the best social contribution (0.146 jobs per 1000 m^3). Similarly, cassava with cultivated area in LJ of 168 ha received irrigation with a volume lower than required (RIS = 0.76) and generated 0.119 jobs per 1000 m^3. Extensive crops such as green coconut, rice, and sugar cane require interventions in irrigation management to increase the number of jobs generated per 1000 m^3.

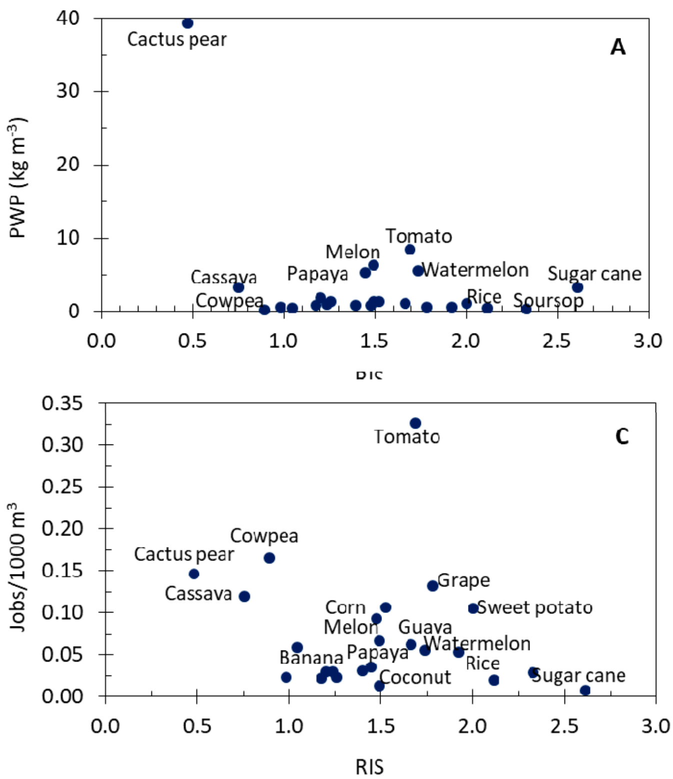

Figure 2. Physical water productivity (**A**), economic water productivity (**B**), and generation of jobs per 1000 m^3 of applied water (**C**), as a function of the relative irrigation supply for some crops selected in the Lower Jaguaribe sub-basin.

The low values of irrigation performance indicators observed in the LJ are aggravated in MJ (0.206 kg m^{-3}) and UJ (0.151 kg m^{-3}), where, for example, a marginal performance of the rice crop irrigated by continuous flooding is observed (PWP = 0.206 kg m^{-3} in MJ and 0.151 kg m^{-3} in MJ). In these two sub-basins, the soils have a sandy texture and are not suitable for rice crop. With continuous flooding, in plots of sandy textured soils, in the irrigated perimeter of Morada Nova (LJ), the average values ranged from 0.178 to 0.224 kg m^{-3}, with gross irrigation volume from 22,600 to 25,900 m^3 ha^{-1} [38]. The authors also add that the different methods of growing the crop by producers somehow limits a more careful analysis of the results obtained for the physical water productivity. Nevertheless, as expected, the textural units of heavier soils were associated with the highest values of PWP. In another study [40], the PWP values in two soil textural units for rice cultivation were lower in sandy loam textural unit compared to the silty clay loam textural unit. In the State of Rio Grande do Sul, the largest rice producing region in Brazil, and in soil classified as *Planossolo Háplico Eutrófico arênico* (Alfisol), it was found PWP ranging from 1.76 to 1.92 kg m^{-3} as a function of the sowing time [41]. For silty-clayey textured soil the PWP values ranged from 0.33 to 1.07 kg m^{-3} [42].

Like rice, the cultivation of sugar cane in LJ, the main producing sub-basin, is receiving an excessive gross volume of irrigation compared to the required volume and has also low physical land productivity, despite the use of advanced irrigation technology. This fact points to the need for using appropriate techniques for agronomic management of the crop and irrigation aiming at increases in PLP, PWP, and EWP. Sugar cane cultivation also has a low social contribution to job creation (0.14 jobs ha^{-1} and 0.007 jobs per 1000 m^3 in LJ).

The average agronomic yield of stems of sugar cane grown under a rainfed regime in northeastern Brazil is around 53,200 kg ha^{-1}, whereas in cultivation under irrigation with center pivot it reaches values higher than 100,000 kg ha^{-1} [43]. Several experiments in different regions of Brazil indicate better agronomic results of sugar cane irrigated compared to those cultivated in the Jaguaribe basin [44–47]. The yields obtained in these studies ranged from 160,000 kg ha^{-1} [44] to 300,463 kg ha^{-1} [47], with total water depths (irrigation plus rainfall) of 1737 and 2830 mm, respectively.

The banana crop occupies a significant area in the Jaguaribe River basin, but it has a relatively low PWP in the three sub-basins (1.32 to 1.77 kg m^{-3}). These values are higher than those observed in other studies with banana crop irrigated by furrows infiltration [48]. However, in a semiarid region of the Minas Gerais state, it was found PWP of up to 4.6 kg m^{-3} for irrigation management based on ET_c fractions, and reduction in the water depth up to 42% of ET_c did not lead to significant reductions in yield [39]. For cultivar "nanicão" in the semiarid region of Paraíba, it was found yields ranging from 20,569 kg ha^{-1} to 31,940 kg ha^{-1}, as a function of irrigation depth, and water productivities between 2.5 kg m^{-3} and 4.1 kg m^{-3}, respectively [49]. It is worth pointing out that the low yields of banana cultivars in areas in the Brazilian semiarid region are partly related to the inadequate nutritional status of the plants [50].

Cowpea is a traditional food of the Northeast region, being produced in the three sub-basins. It has reduced values of RIS (less than 1 in LJ and MJ and 1.06 in UJ) and shows good land productivity in both sub-basins, with 1.92 kg ha^{-1} as the maximum PLP found in the basin. In this case, the problem is the low economic value of the product, which reduces ELP and EWP. It is the case, therefore, of adopting cultivation strategies, scheduling the production, in order to achieve better prices in the market, increasing the attractiveness of the activity. It is worth pointing out that the physical land productivity reported for cowpea in the Jaguaribe River basin were similar or higher than those obtained in field trials in other regions of Brazil [51–53].

In regions with water scarcity, crops with high PWP should be preferred, although this is not the only factor. Crops such as grains, with high energy value, and crops with high protein content may have a low absolute value of PWP, but their nutritional value is more important and this should be considered in their evaluation for drought-prone areas [22].

In general, the values of PWP of irrigated crops in the Jaguaribe River basin should be improved. The literature presents several alternatives to increase PWP [23,35,54–56], which can be summarized as follows: (i) increase the harvest index through genetic improvement of the crop or management; (ii) reduce the transpiration rate by selecting improved species, selection of variety, or plant breeding; (iii) maximize dry matter production through the improvement of soil fertility, weed control, and planting optimization; and (iv) increase the transpiration component of the water balance at the expense of the reduction of other components, such as: (a) reduction of evaporation by the use of mulch on soil surface, minimum soil tillage, and partial wetting of the soil surface; (b) reduction of deep drainage, avoiding excessive wetting of the root zone, and minimizing the need for leaching to control salinity; (c) reduction of surface runoff using crop residues, soil conservation techniques and prevent soil compaction and the formation of surface crusts; and (d) gradual imposition of soil water deficit.

4.3. Performance Index of Irrigated Crops in the Jaguaribe River Basin

Table 6 presents performance indexes for irrigated crops in each sub-basin considering two scenarios previously defined: Scenario A represents high water scarcity, with a previous decision to save permanent crops, ensure food security and maintain labor employment, assigning low values to α (Equation (14)) for ELPR (0.10), EWPR (0.10), and LLABR (0.10), and high values to cycle (0.10), PLPR (0.20), PWPR (0.20), and WLABR (0.20). Another scenario, B, represented a condition of low water scarcity in which the aim is to maximize yield. In this scenario, values of α were defined so as to favor other indicators, that is, low values of PLPR (0.10), PWPR (0.10), and WLABR (0.10), keeping high values for cycle (0.10), ELPR (0.20), EWPR (0.20), and LLABR (0.20). The result is a ranking of distinct crops for each scenario, ordered according to the performance index (PI).

Table 6. Performance index (PI) of irrigated crops in the Jaguaribe River basin, considering two water restriction scenarios.

	(PI) Scenario A			(PI) Scenario B		
Crops	**LJ ***	**MJ**	**UJ**	**LJ**	**MJ**	**UJ**
Avocado	0.195	—	0.195	0.224	—	0.225
Barbados cherry	0.275	0.266	—	0.309	0.302	—
Rice	0.127	0.176	0.143	0.139	0.187	0.162
Custard apple	0.244	—	—	0.326	—	—
Banana	0.199	0.515	0.424	0.235	0.474	0.523
Sweet potato	0.195	0.543	—	0.221	0.504	—
Cashew	0.160	—	—	0.188	—	—
Sugar cane	0.164	—	0.387	0.136	—	0.289
Green coconut	0.156	0.357	0.332	0.162	0.293	0.271
Cowpea	0.198	0.195	0.214	0.191	0.189	0.212
Guava	0.227	0.563	0.342	0.267	0.619	0.390
Soursop	0.176	—	—	0.215	—	—
Orange	0.165	0.162	0.197	0.177	0.175	0.218
Lemon	0.152	0.214	0.182	0.162	0.194	0.190
Cassava	0.263	0.582	0.530	0.284	0.594	0.569
Papaya	0.328	—	0.545	0.376	—	0.492
Mango	0.182	0.293	—	0.211	0.281	—
Passion fruit	0.308	—	0.334	0.465	—	0.340
Watermelon	0.202	—	0.470	0.171	—	0.409
Melon	0.263	—	—	0.273	—	—
Green corn	0.173	0.219	0.238	0.191	0.226	0.282
Cactus pear	0.746	—	—	0.682	—	—
Tomato	0.652	0.950	0.950	0.771	0.950	0.950
Grape	0.319	—	—	0.398	—	—

* LJ (Lower Jaguaribe), MJ (Medium Jaguaribe), and UJ (Upper Jaguaribe).

It is observed that, in LJ, cactus pear, tomato, papaya, grape, and passion fruit are the five crops at the top of the ranking as priorities for irrigation in any of the two scenarios analyzed, with PI above 0.3, only in different orders. Sugar cane, cashew, coconut, lemon, and rice appear among crops with low priority for irrigation in these scenarios, with PI much lower than 0.3. Rice is particularly the last priority under water scarcity conditions and the penultimate in case of low water scarcity. Rice and sugar cane crops have significant areas of cultivation in LJ, but reveal low priority for irrigation, especially because they have very low ELP, EWP, and contribution to labor employment, in addition to a high value of RIS.

In MJ, in the two hypothetical scenarios analyzed, tomato, cassava, guava, sweet potato, and banana crops could be encouraged because they have PI above 0.3. Incentives should no longer be given to cowpea, rice, and orange crops, which have low PI (less than 0.3). In UJ, in the two scenarios studied, the best performances were observed with tomato, papaya, cassava, watermelon, and banana crops, with PI above 0.3, although in different orders. The worst performances were shown by cowpea, orange, avocado, lemon, and rice crops, with PI below 0.3. It is worth pointing out that the rice crop shows marginal performance in the two scenarios analyzed and in all sub-basins. However, there is room for improving the performance index, for example by adopting intermittent flooding irrigation and avoiding cultivation in light-textured soils [35,38], mainly with a view to reducing the volume of irrigation applied.

In general, most irrigated crops in the Jaguaribe River basin require specialized technical assistance in irrigation management, in agronomic technologies that can increase land productivity and training of irrigators. To improve irrigation management, it is necessary to establish procedures for evaluating the performance of the systems, define and identify the objectives, and set the goals. Performance indicators should be used to monitor the achievement of the goals and, therefore, of the objectives [57]. A wise choice of production goal is crucial to increase the profit of the farmer [3]. For some forage crops, maximum biomass can be an appropriate production goal. For cereals and other crops whose yield is a fraction of biomass, achieving the maximum marketable yield may be the correct production goal. Still, the farmer usually seeks as much money as possible and sometimes achieving maximum potential yield is not the most lucrative option.

Overall, the irrigation water management strategies in the Jaguaribe River basin illustrate that there are opportunities for success with more ambitious interventions to reduce water consumption and increase yield, such as those presented in other studies [20,23,24,35,54–56,58–60]. In addition, water management in agriculture, on all scales, linked to the preservation of environmental flows, would greatly help the intricate task of reducing poverty and increasing agricultural yield [58]. Other important strategies, such as the inclusion of soil fertility optimization and varieties of crops, are necessary to maximize crop water productivity.

5. Conclusions

The Jaguaribe River basin is under a tropical semiarid climate, with an important restriction on the availability of water resources. In this work, the performance of irrigated agriculture was analyzed using water, production, economic and social security criteria. A low performance index (below 0.3) has always been associated with inadequacy of more than one security indicator. In general, the results indicate the need to reduce the volume of water applied by irrigation and increase yield, income, and jobs. Several crops with significant cultivated areas and, therefore, requiring high volume of irrigation, such as rice, banana, sugar cane, and green coconut, require technical interventions related to the management of the soil–water–plant system aiming to improve their yield with less water. The success of the application of modern agricultural techniques also depends on institutional actions aimed at stimulating technical assistance and the dissemination of knowledge, education and training of irrigators, as well as the promotion of incentives for the efficient use of water and penalties for inefficient use. Under conditions of strong water restrictions and great competition for water use, as is the case in the Jaguaribe River basin, priority should be given to crops that have performance indexes higher than 0.3, especially those with significant irrigated areas. The study presented here for irrigated agriculture in the Jaguaribe River basin may support public policies in the field of irrigation and agronomic techniques that are necessary to improve the performance of agricultural production under semi-aridity conditions.

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